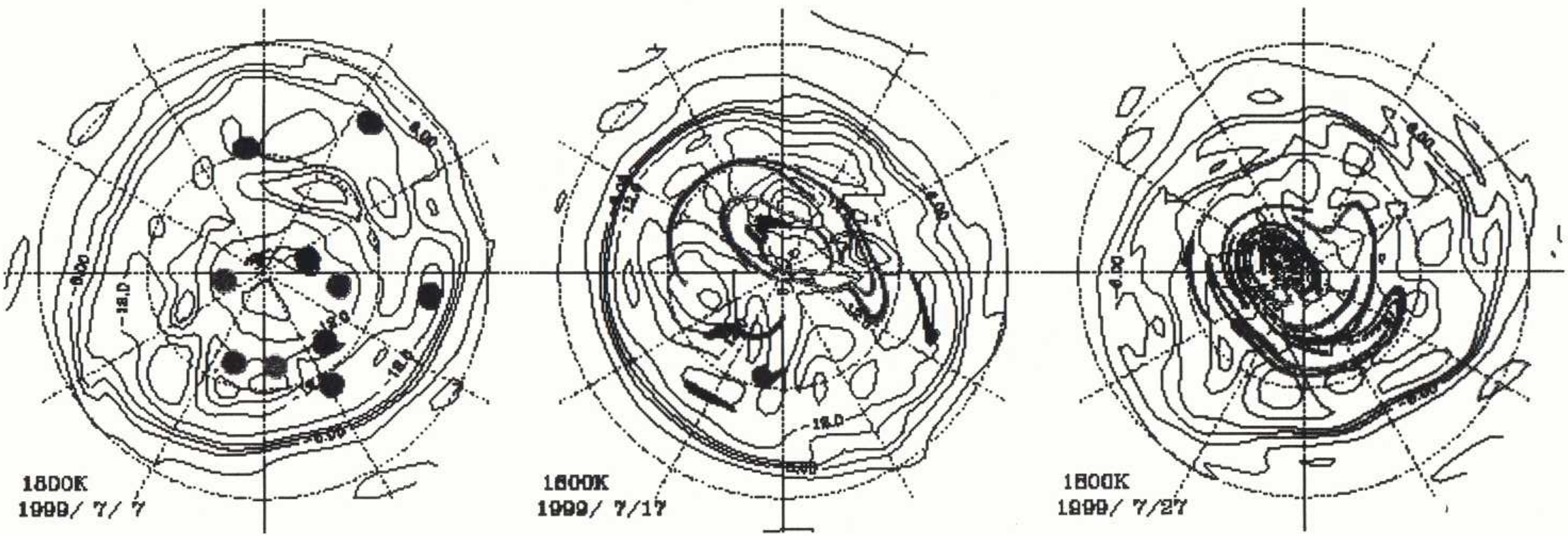

[Yoden & Mizuta, 2000]

Tracer Mix-down Problem

- Downscale tracer variance cascade (Measured in lower stratosphere (2D) using Yaglom's $\langle \delta u_L \, \delta\theta \, \delta\theta \rangle = -2\epsilon_\theta r$ [Lindborg & Cho, Phys. Rev. Lett., 2000])

Stretching & folding
by large-scale flow

Downscale
cascade

chaotic mixing
by multiple gravity waves

3D turbulence
(intermittent)

Molecular diffusion

Mixing time & scale?

- Vertical dimension is key.

[Haynes & Anglade, 1997]

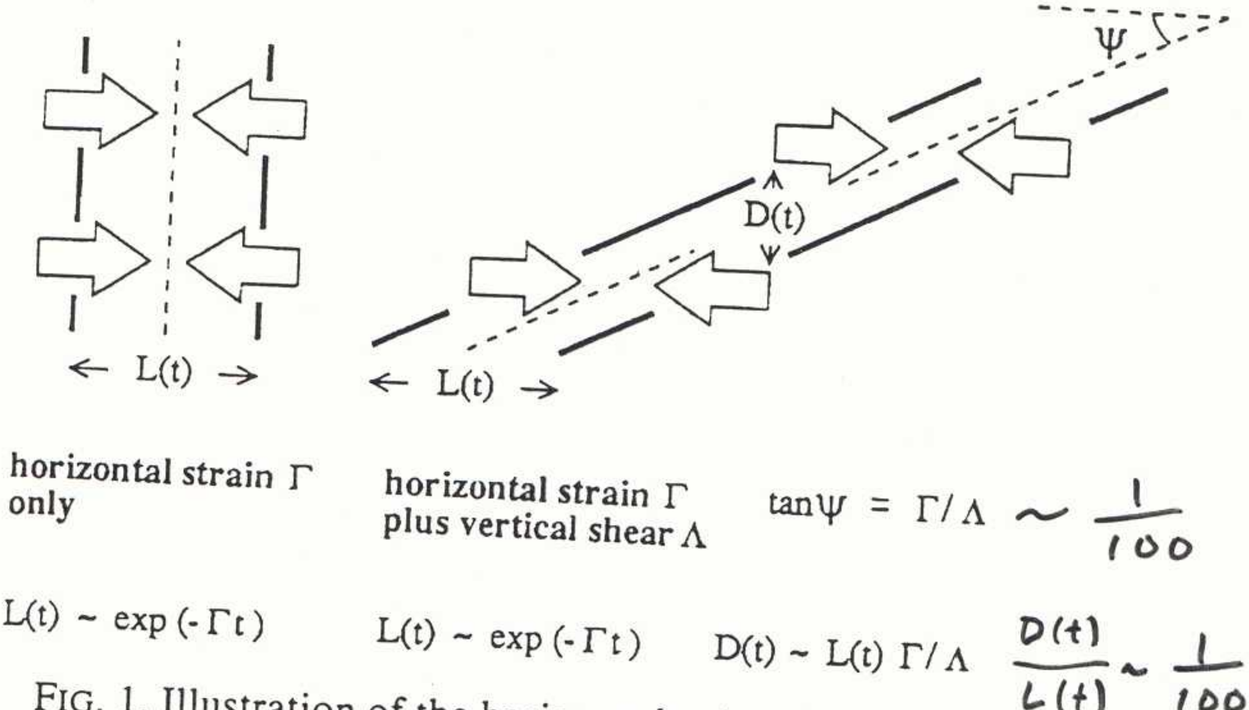

FIG. 1. Illustration of the basic mechanism by which vertical scales are reduced in a flow containing a combination of horizontal strain and vertical shear. The effect is shown of such a flow on a tracer sheet, with tracer contours represented by the bold lines. The flow could be that considered in section 2, in which case the view is along the x-axis, which is the axis of extension for this flow. The left-hand panel shows the effect of a flow including horizontal strain alone. The horizontal thickness L of the tracer sheet is reduced in time as $e^{-\Gamma t}$, where Γ is the horizontal strain rate. The right-hand panel shows the effect when a flow in the y direction with shear Λ in z is added. The axis of the strain field is now tilted to the vertical at angle $\tan^{-1}(\Lambda/\Gamma)$, as is the resulting tracer sheet. The horizontal thickness L and the vertical thickness D therefore both decrease as $e^{-\Gamma t}$ and stay in the aspect ratio Λ/Γ. Calculations in sections 3 and 4 show how this effect persists when the horizontal strain and vertical shear fields are time dependent.

⇒ "Layers" thin down to mixing limit before "filaments" do.

with time and diffusive decay becomes important when this term $\sim \kappa^{-1}$. If κ is sufficiently small, then the time at which this occurs will be determined by the first term inside the bracket, which is most rapidly growing for

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Temperature "Sheets"

- Very thin regions of rapid temperature rise with height.
- Observed in oceans, lakes, atmosphere.

  [Free atmosphere obs.: Dalaudier et al., 1994]

  → Motivation: Clear-air radar scatter.
- Typical values: Thickness ~ 3–20 m

  $\Delta T \sim 0.2 - 0.8$ K
- Simultaneous humidity sheet obs.:

  Muschinski & Wode, 1998.

⇒ Resistance to mixing at small scales.

- How are they formed?
- Characterization & statistics?

[Dalaudier et al., 1994]

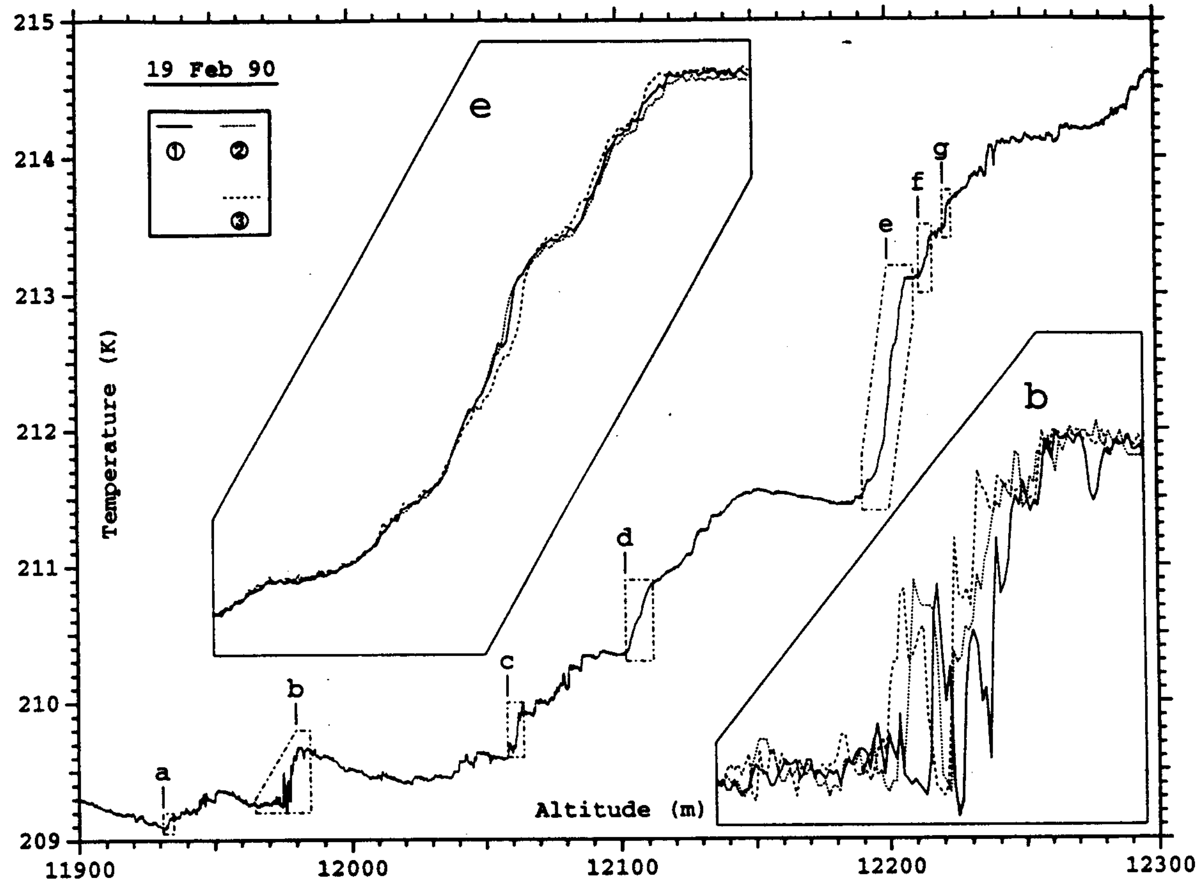


FIG. 1. High-resolution (20 cm) temperature profile, just above the tropopause. Boxes marked with letters (a . . . g) contain examples of sheets. Two close-ups of sheets "b" and "e" are displayed with the three profiles measured on the main gondola. The relative disposition of the sensors and the line style used are shown in the upper-left corner (distance ①② = distance ②③ = 1 m). Ongoing mixing is clearly present in the sheet "b."

Southern France, end of winter.

We first tried to determine if the gradients observed within these sheets constituted a distinct population in the histogram of the vertical gradients. But we found that nothing special distinguishes them from any other gradient, and that they merely constitute the upper tail of the gradient distribution that is monotonic (and strongly decreasing) in this region. This conclusion implies that the distinction between a sheet and another gradient is somewhat arbitrary, as discussed further below. The same conclusion was reached by Desaubies and Gregg (1981) on the basis of oceanic high-resolution temperature measurements. Their Fig. 4, showing the (finite difference) temperature gradient distributions for various vertical spacings, illustrates quantitatively this point. However, the observed characteristics of the sheets cannot be accounted for only by the properties of the gradient distribution. For example, their thinness is an independent (and important) characteristic, as well as their spatial and temporal distribution.

We will present below some characteristics of the sheets that we could deduce from the dataset analyzed, and we will discuss their potential impact on propagation phenomena. We intentionally avoid any theoretical speculation about their nature or their generation mechanism, this question being a separate, and perhaps controversial, subject. However, the interested reader can find a good discussion of some possible mechanisms (for the oceanic case) in Desaubies and Gregg (1981).

a. Examples of stratospheric sheets

Before giving a more precise definition of what we call a sheet, we will look at some examples in order to get an intuitive idea of what they are. Figure 1 displays a section of temperature profile with a high vertical resolution (0.2 m), as observed with a balloonborne gondola, just above the tropopause. On this profile, some regions with strongly positive (vertical) temperature gradients are labeled with letters ("a" . . . "g"). These regions are examples of what we call sheets; we will explain below how they were selected. Figure 1 also contains two close-ups of gradients "b" and "e" where the profiles observed by three temperature sensors one meter apart (one pair horizontal and one pair vertical, as indicated on the upper left corner of Fig. 1) are shown. The comparison of the three profiles gives important clues about the structure of the sheets. Note that, owing to the wind differences between bal-

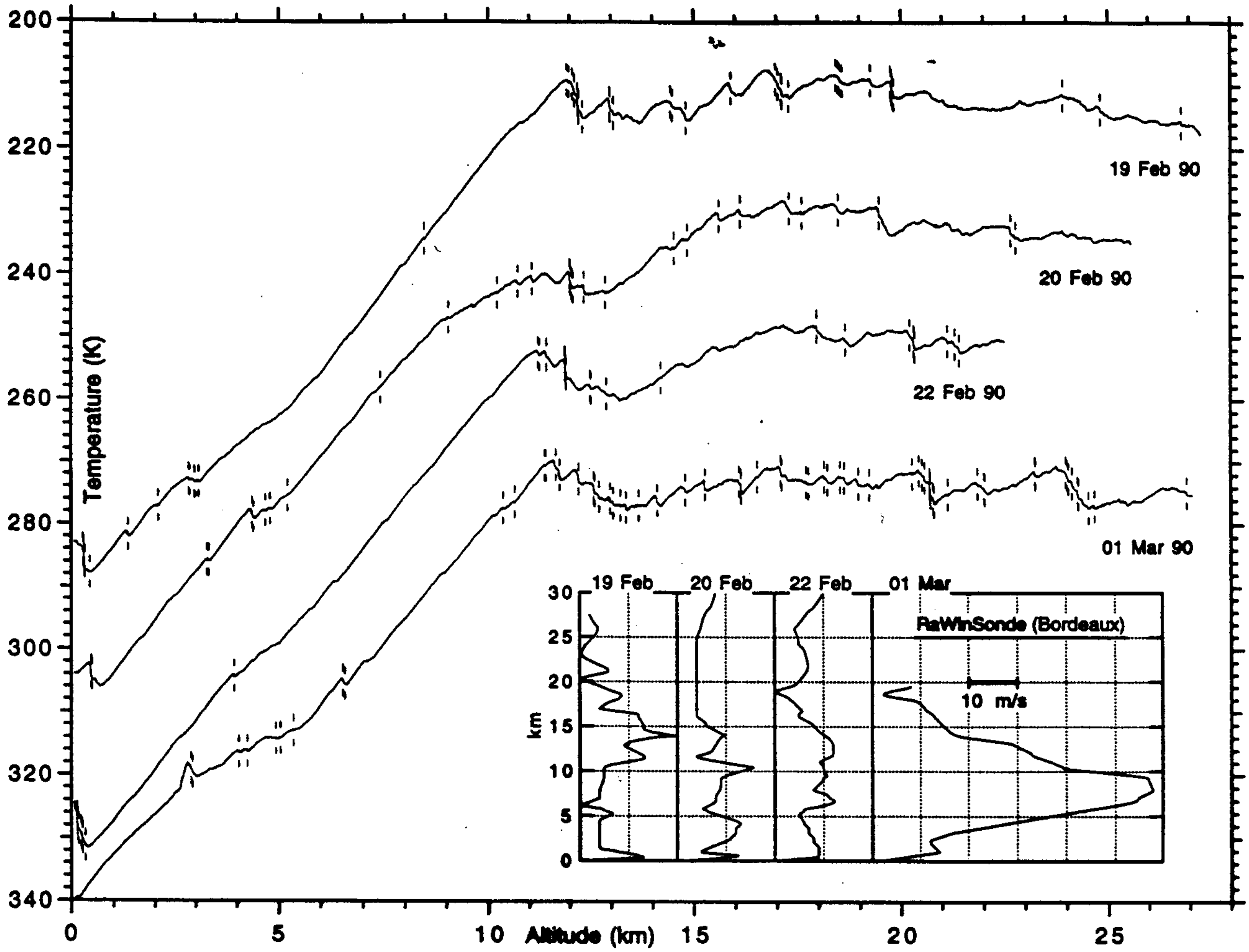


FIG. 2. The four temperature profiles measured during the four balloon ascents (successive profiles are offset by steps of 20 K). The positions of the sheets are indicated by small ticks. The sheets tend to occur in groups in regions of overall strong static stability. The fourth profile (1 March), obtained during disturbed meteorological conditions, contains more sheets than the previous ones. The small box in the lower-right corner displays the four wind profiles obtained from rawinsondes launched from Bordeaux at 2400 UTC. The jet stream during the fourth night exceeded 55 m s^{-1}.

quires that the generation mechanism of the sheets be understood.

If we restrict attention to regions where the temperature increases with altitude (the gradient being calculated as for N_{BV}^2), the contribution of the sheets to this increase is between 16% and 46% in the troposphere and between 22% and 50% in the lower stratosphere. By contrast, the contribution of the sheets to the altitude increase (in the same regions where $dT/dz > 0$) is only between 2% and 14% in the troposphere and between 3% and 17% in the lower stratosphere. In other words, the sheets occupy a small fraction of the profiles, but they contribute to a large fraction of the temperature increase.

b. Thickness and amplitude distribution

Figure 3 represents, in log–log coordinates, the thickness Δz of the sheets (for the four flights) versus their amplitude ΔT. Three different markers were used to distinguish three atmospheric regions: the stable boundary layer, the troposphere, and the stratosphere. Four oblique lines indicate constant values of the average gradient, from top left to bottom right $\Delta T/\Delta z$ = 10, 30, 100, 300 K/km. Most stratospheric sheets are steeper than 30 K/km and all tropospheric ones are steeper than 10 K/km, these lower limits being consequences of the selection process. This can be regarded more or less as a definition of the sheets. As already noted in the Introduction, the distribution of atmospheric temperature gradients is continuous, and we look here only at its upper tail.

More informative is the fact that stratospheric sheets can reach 300 K/km, while tropospheric ones reach 200 K/km. However, it should be noted that such extreme values are reached only by the thinnest (less than 2 m) ones. Another characteristic that distinguishes tropospheric and stratospheric sheets is their maximum amplitude: in the stratosphere, it can exceed 2 K, while in the troposphere it is smaller than 1 K and even 0.5 K for most of them. The sheets observed in the stable boundary layer seem to behave exactly like strato-

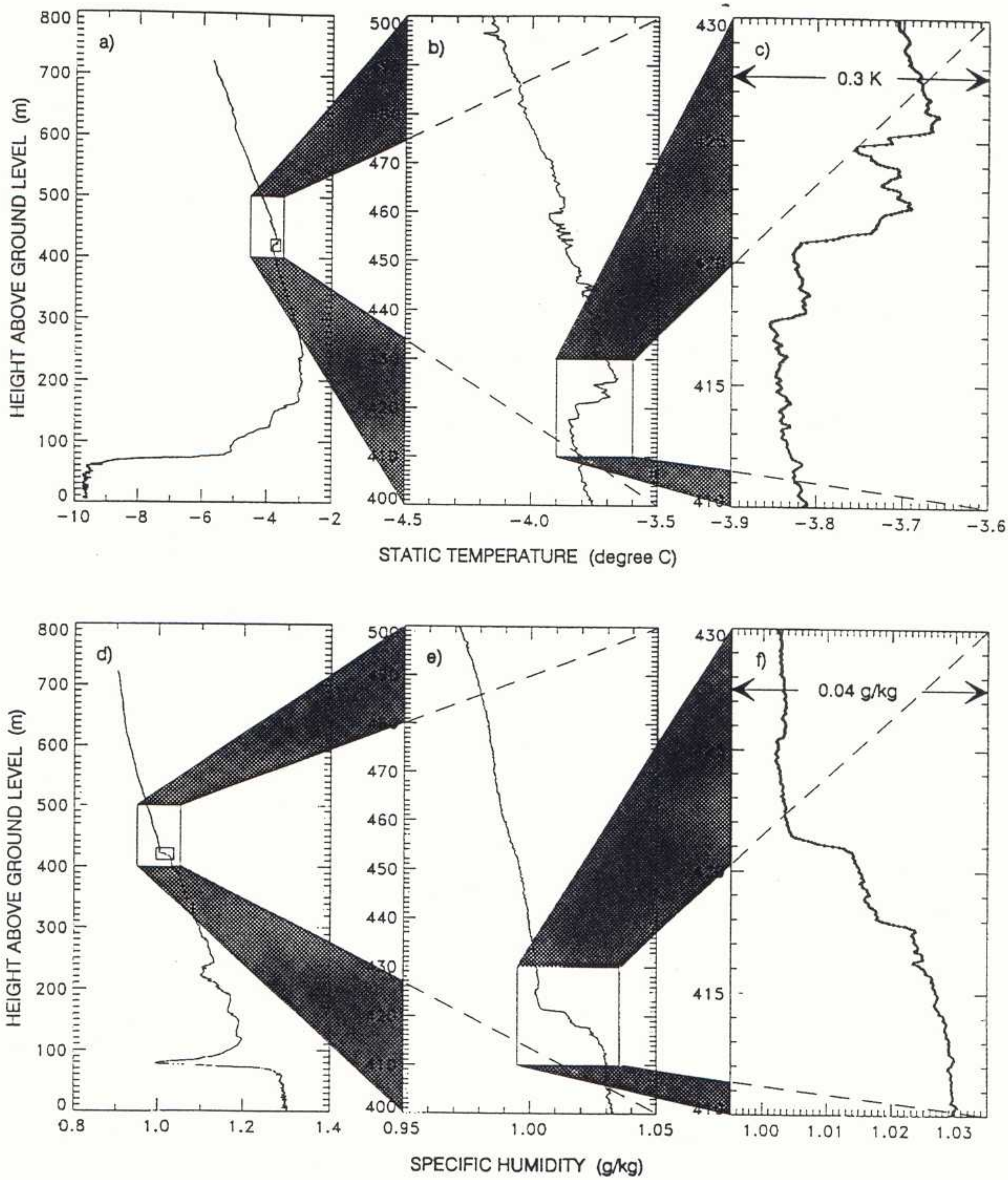


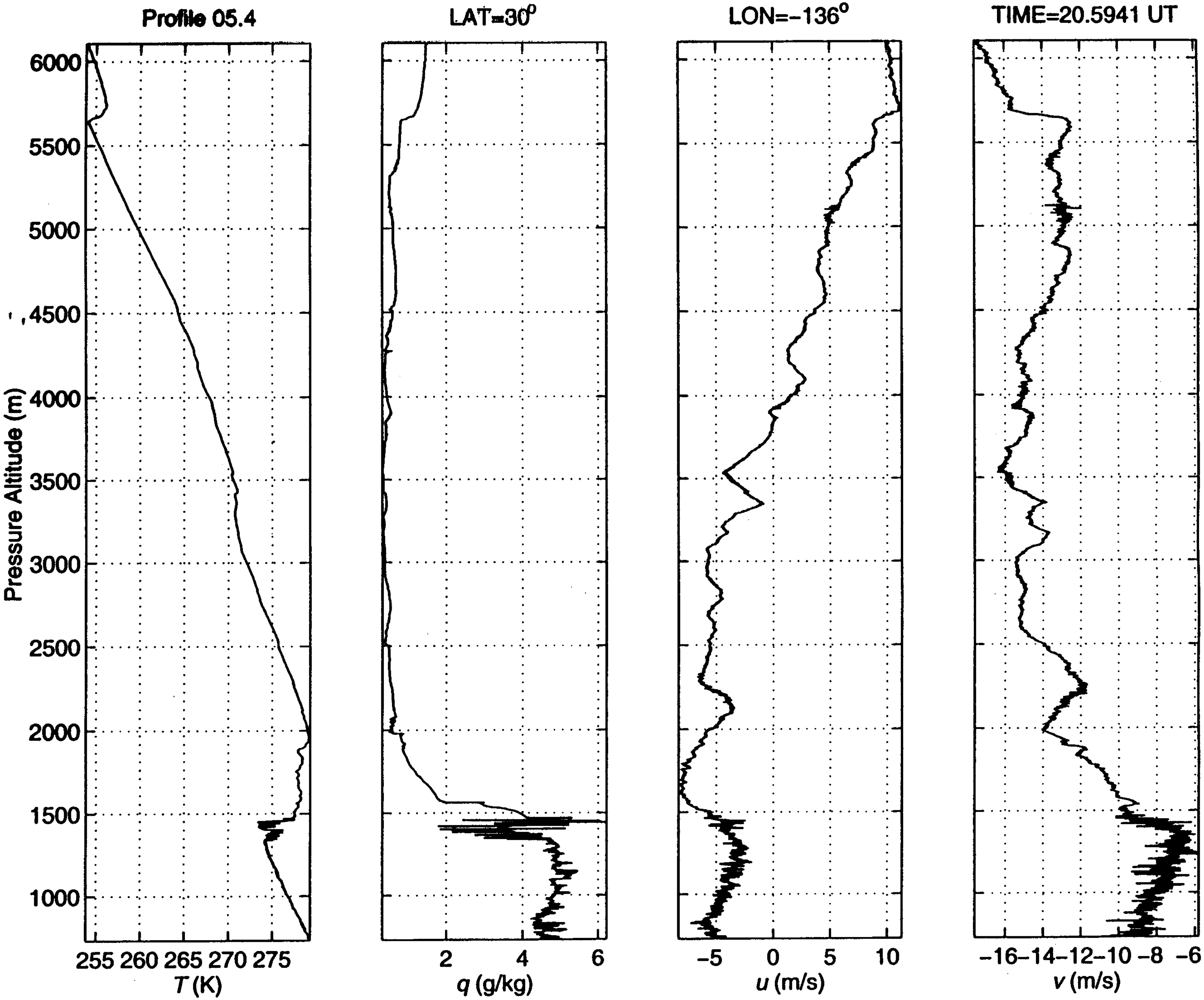
FIG. 5. Close-up of a group of submeter temperature (a)–(c) and humidity sheets (d)–(f), respectively, observed during leg S1. The sheets, corresponding to a strong vertical temperature gradient, can be clearly detected between 417 m and 426 m AGL.

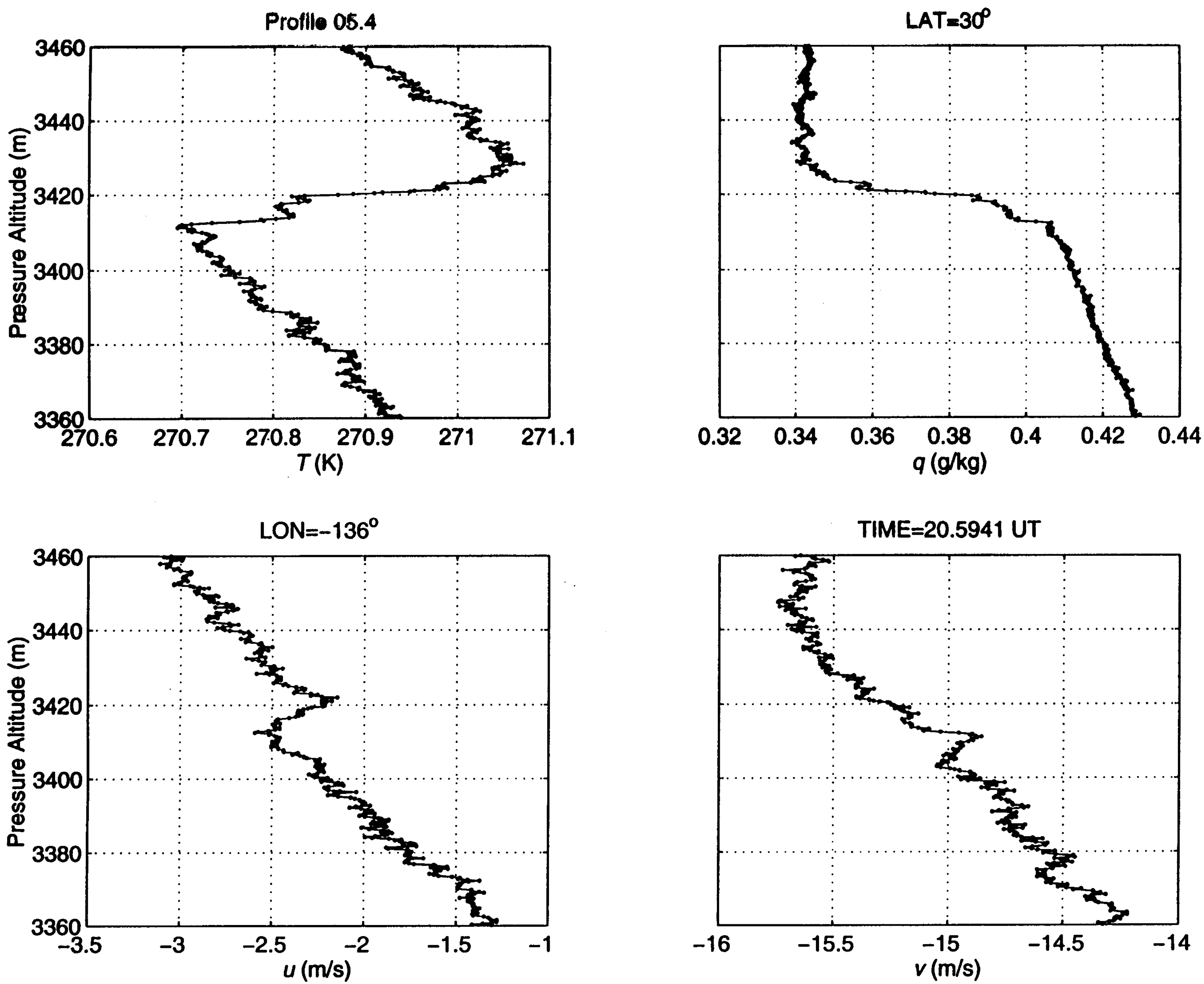
midity q ranges between 1.002×10^{-3} and 1.030×10^{-3}, the zonal wind u between 6.5 m s^{-1} and 7.3 m s^{-1}, and the meridional wind v between -0.1 m s^{-1} and 0.3 m s^{-1}. At the altitudes of the temperature sheets, there are also sudden changes in the specific humidity (see Figs. 6a and 6b). At 418 m AGL, q decreases from 1.023×10^{-3} to 1.018×10^{-3}, at 421 m AGL, q decreases from 1.013×10^{-3} to 1.005×10^{-3}. Between 425 m and 426 m AGL, however, there is an *increase* from 1.002×10^{-3} to 1.003×10^{-3}.

One of the most beautiful examples of coexisting temperature and humidity sheets that we found in our da-

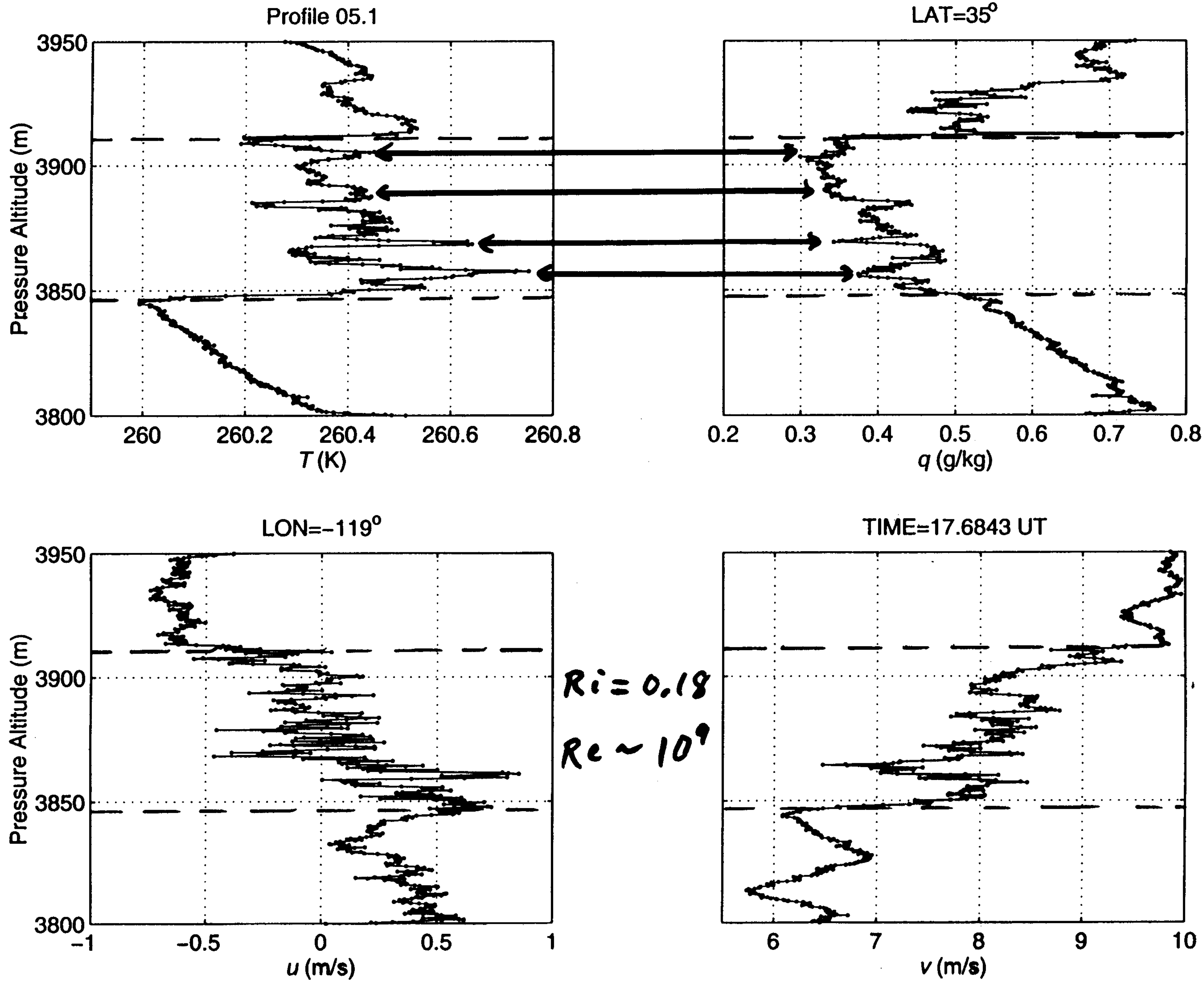
off east coast of Greenland in autumn

TRACE-P P-3B TAMMS





stretching/shearing by large-scale flow?


Profile 05.1
LAT=35°
LON=−119°
TIME=17.6843 UT
Pressure Altitude (m)
T (K)
q (g/kg)
u (m/s)
v (m/s)
Ri = 0.18
Re ~ 10^9